Renewable and Sustainable Energy Reviews 16 (2012) 5295–5308

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

LCA of second generation bioethanol: A review and some issues to be resolved for good LCA practice

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A R T I C L E I N F O

Article history:
Received 9 December 2011
Received in revised form
19 April 2012
Accepted 20 April 2012
Available online 4 July 2012

Keywords:
Agriculture
Fermentation
Life Cycle Assessment
Lignocellulosic biomass
Second generation bioethanol
Transportation biofuel

A B S T R A C T

This paper aims at reviewing the life cycle assessment (LCA) literature on second generation bioethanol based on lignocellulosic biomass and at identifying issues to be resolved for good LCA practice. Reviews are carried out on respective LCA studies published over the last six years. We use the classification of lignocellulosic biomass to define system boundaries, so that the comparison among LCA results can be thoroughly assessed based on identified system components. A basis for attributing environmental burden for different biomass feedstocks is also suggested. Despite the non-homogeneous systems, we conclude that second generation bioethanol performs better than fossil fuel at least for the two most studied impact categories, net energy output and global warming. For the latter category, carbon sequestration at the biomass generation stage can even consistently offset the GHG emissions from all parts of the life cycle chains at high ethanol percentage ($\geq$85%). The aspect of biogenic carbon and agrochemical input for energy crops and biomass residues, and the effect of removal of the latter from soil have not been treated consistently. In contrast, the exclusion of upstream chain of biomass waste feedstocks is observed in practice. The bioethanol conversion process is mostly based on simultaneous saccharification and co-fermentation, characterized by high yield and low energy input. In this regard, the LCA results tend to under estimate the real impacts of the current technology. The choice of allocation methods strongly influences the final results, particularly when economic value is used as a reference. Substitution of avoided burden seems to be the most popular allocation method in practice, followed by partition based on mass, energy, and economic values.

Contents

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http://dx.doi.org/10.1016/j.rser.2012.04.035

1. Introduction

Over the last ten years, there has been a dramatic increase in bioethanol production from 16.9 billion liters in 2000 to 72 billion liters in 2009 [1]. The production is dominated by the USA and Brazil and based on corn grain and sugarcane syrup, respectively. The bioethanol product is mostly used as an alternative transportation biofuel in response to escalating prices of fossil oil, due to limited supplies, and global warming. This development however has been retarded by the growing concerns of competition with food availability, actual net energy output, and consequences related to land-use change [2]. The competition with food in the USA is reflected by reallocation of 20% US corn to ethanol production in 2006, and this allocation has been partially blamed for the increase of food prices between 2003 and 2008 [1]. In Brazil, the high production cost for sugarcane ethanol is governed by the price of raw materials that account for 70% of the total production cost [3]. Given this background, there is a need to explore alternative feedstocks such as non-edible lignocellulosic biomass. This type of feedstock is available in abundance in many countries/regions, and its utilization only competes with food resources to a limited extent. In many cases, this kind of feedstock does not need fertile land or extensive maintenance for its generation, so that the potential environmental and social impacts of the biofuel system are expected to reduce to a great extent. Another motivation to explore such lignocellulosic based biofuels is to improve the emission balance of greenhouse gases (GHGs). In this paper, we follow a terminology of the bioethanol derived from non-edible lignocellulosic biomass as second generation bioethanol [4–6].

Although there is much potential for lignocellulosic feedtocks, the realization for bioethanol production target in many countries has been so far discouraging. In the US for example, high production costs make bioethanol as a transportation biofuel still prohibitively expensive [7]. The reason for these high production costs is partly related to the characteristic of lignocellulosic feedstock that need advanced processing technologies including pretreatment, hydrolysis of cellulose and hemicelluloses, and co-fermentation of the resulted sugars [8]. As a result, recently, the US Government has reduced the cellulosic ethanol mandate from 250 to only 6 million gallon per year [7]. This suggests that the conversion technology for bioethanol production at the commercial stage remains insufficient. More time is still needed for developing advanced and efficient technology. In conclusion, Phalan [9] mentions that the promise of replacing fossil oils with biofuels may still not be applicable to a great extent in some countries, but can overall help to diversify supply and reduce our dependence on fossil fuels.

Life cycle assessment (LCA) is a method to evaluate the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle [10]. Despite the fact that there is an ISO standard (ISO 14040, 2006), the application of LCA in practice is not always straight forward and indeed LCA studies on similar products yield diverging results. This is particularly true when studying agricultural systems for which the parameters vary depending on their specific conditions. Important aspects pertaining to the LCA methodology of biofuel system are the definition of the system boundary, the choice of functional unit, the choice of allocation methods, the treatment of biogenic carbon, the selection of impact categories, the choice of reference system, and the effect of biomass removal from soils [11–13]. Recent review papers have shown some conflicting LCA outcomes when using different allocation methods, in particular the use of economic values as opposed to physical properties as a basis to allocate burdens from multi-output processes [12]. The same authors also pointed out the importance of including or excluding biogenic carbon in the outcome of the LCA results. In addition, many LCA studies of cellulosic bioethanol system have not included important system components, particularly in the agricultural chain where the type of feedstocks vary (energy crops, biomass residues, and biomass wastes) and in bioethanol production where different levels of technology (current and future scenarios) are adopted [13,14]. This creates problem when comparing different bioethanol systems.

The above-mentioned reviews on LCA of biofuel systems [12,13] and the earlier ones [15,16] often cannot easily conclude if there are benefits with biofuel over fossil fuel. It is even not possible to clearly differentiate the performance between first and second generation biofuels, or among different energy crops, biomass residues and wastes [12]. These studies cover a wide range of variables, such as different feedstock types (edible and non-edible resources) and biofuel types (biodiesel and bioethanol). In this context, variation in the assessment results may be caused by not only the classical problem related to the freedom to choose specific LCA methodology, but also by differences in the real world situation [12]. These reasons are mixed and not easily differentiated from each other, creating complication in the comparison and interpretation of LCA results. The current review therefore limits its coverage only to LCA studies describing second generation bioethanol based on lignocellulosic feedstock, so that a comparison can be made on a rather homogeneous system. To date, at least three review papers on bioethanol LCAs specifically based on lignocellulosic biomass have been published [11,17,18], but with a rather limited number of cases. Our review conveys a more comprehensive number of papers on the LCAs of lignocellulosic bioethanol system published over the last six years. Also, our study identifies the coverage of system components within the life cycle chains in relation to biomass feedstock specifications, so that the comparison among LCA results can be thoroughly assessed based on identified system components.

Ultimately, this paper aims at reviewing the LCA literature on second generation bioethanol based on lignocellulosic biomass and at identifying issues to be resolved for good LCA practice, particularly with respect to discrepancies in methodological and practical approaches. Emphasis has been put on system definitions in relation to feedstock specifications (energy crops, biomass residues, and biomass wastes), levels of bioethanol conversion technology (current and future scenarios), bioethanol use as transportation fuel, functional units, allocation methods, and included impact categories. The outcome aims to provide decision makers with an increased understanding of the status of second generation bioethanol based on most studied impact categories. It may also aid researchers to develop a LCA framework for the bioethanol system with correct parameters considering typical problems encountered in the agricultural and bioethanol production chains.

2. Methods

This study reviewed 22 papers published between 2005 and 2011, covering 14 different lignocellulosic biomass feedstocks. The selection of the papers were based on previous bioethanol LCA reviews [12,13] and more recent publications using Boolean search of Web of Sciences database and Google Scholars. Only peer-reviewed journal articles are included in this current study. They are all LCA studies or claimed to use a life cycle approach to assess environmental impacts, described bioethanol as the system product and used lignocellulosic biomass as the raw materials.

Data from the reviewed papers is presented in Figs. 2–6. The references to these survey results can be found in Tables A.1–A.4 of Appendix A.

The analysis is initiated by presenting a general framework of the expected system components of a complete (cradle to grave) bioethanol system. This framework is then used as a basis for a critical assessment, particularly to seek an explanation as why an LCA study of the same feedstock can end up with different outcomes. Considering data availability, the comparison of the LCA results in terms of environmental impacts of the bioethanol system is limited to only two impact categories that are mostly studied by the reviewed papers, global warming and net energy output. Other important aspects discussed in detail are carbon sequestration, agrochemical input, the effect of biomass removal, biomass transport, enzyme production, bioethanol conversion processes, and bioethanol use as transportation fuel.

3. LCA framework for the bioethanol system

The system boundary of the bioethanol system is defined so that at least the agricultural chain and the bioethanol production are included as a cradle to gate boundary, with additional bioethanol use in the case of a cradle to grave boundary. The set of included processes need to be defined precisely, so that there is a firm basis to properly describe the bioethanol system for the different biomass feedstocks. The importance of functional units, allocation methods, and choice of impact categories is discussed at the end of this section. All of these factors, in turn, will cause variation in the overall impact assessment results of the second generation bioethanol. It is found that the main conversion technology to produce ethanol in the 22 reviewed papers is through fermentation routes, mostly preceded by pretreatment and hydrolysis steps, except two papers [4,19] preceded by gasification to produce Syngas followed by direct fermentation or catalytic conversion. A number of separation and purification steps are provided to bring the ethanol concentration to 99.5% (dry ethanol), after which it is then blended with gasoline before being finally used as a transportation fuel (see Table A.2 of Appendix A). Therefore, the main element of the bioethanol system is as illustrated in Fig. 1.

3.1. Feedstock classification

An important feature of the 2nd generation bioethanol as compared to the 1st generation is in the type of feedstock use. The 1st generation bioethanol uses edible sugar and starch as the raw materials, while the 2nd generation bioethanol uses non-edible lignocellulosic biomass. Lignocellulosic biomass refers to plant biomass consisting of cellulose, hemicellulose, and lignin. The term biomass is often used in a broader meaning. For example, Lal [20] adopts a definition of biomass as renewable organic matter including plant materials, animal product and manure, food processing and forestry by-products, and urban wastes. In this review we will be concerned only with the biomass containing cellulosic materials as potential bioethanol feedstock that may originate from agriculture, plantation, forestry, grasses, or wastes. At the level of biomass generation chains (agriculture, post-harvest processing, or other industrial activities), feedstock classification will bring specific consequences on the way environmental burden is to be attributed. From the LCA methodology point of view, it is important to set a criterion as to how the burden will be attributed to different feedstocks. In this current study, the following guideline for three different feedstock types is proposed.

Energy crops are crops grown primarily to provide a feedstock for energy production [21], included in this category are those generated from agricultural activities and forest log [13]. In this case, all or most parts of the crops are used as the feedstock for bioethanol production. To avoid excess environmental burden related to agricultural chain, the types of energy crops grown are suggested to use high yielding species [13] and require minimal maintenance [22] so that it can survive in marginal or degraded lands. In the case of dedicated energy crops grown on productive soil, there will certainly be direct land-use impact. Also, if there is the possibility of competition for land use with other crops, indirect land-use consequences should be included.

Biomass residues are lignocellulosic biomass generated in the plantation, from post-harvest processing, or from other activities. The first group is known as crop residues; these are parts of plants usually left in the agricultural fields after harvest [20,21], including forest residues (wood pieces leftover after timber extraction). As a physical buffer, crop residues protect the soil from direct impacts of rain, wind, and sunlight, leading to improved soil structure, reduced water runoff and soil erosion. Crop residues also contribute to soil organic matter (carbon and other nutrients), soil microbial biodiversity, and soil carbon sequestration

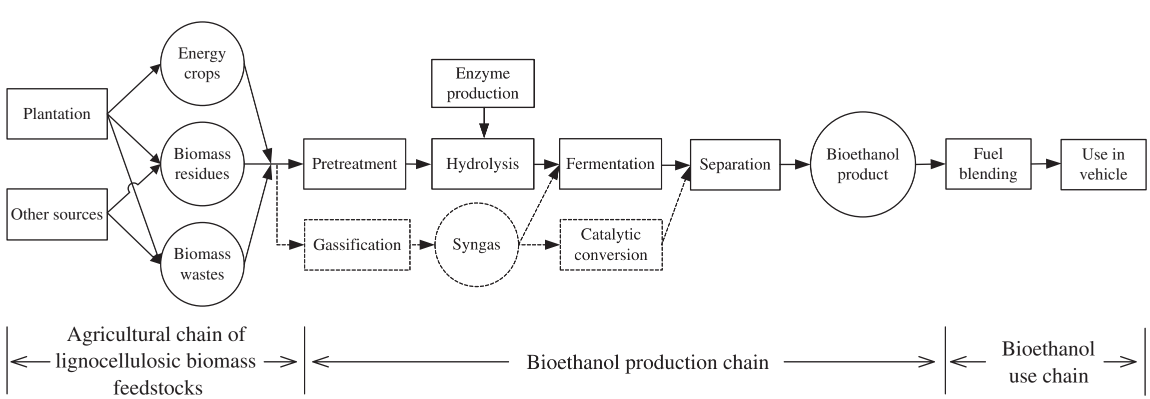

Fig. 1. The system components of the life cycle of bioethanol system. Dashed areas denote minor ethanol conversion routes.

[20]. In addition to their function to maintain in-situ soil quality, off-site competing uses of the biomass residues include animal feed, fiber, industrial raw materials, and energy feedstocks. In conclusion, biomass residues are not the main products, but may have economic value due to several potential uses. Indiscriminate removal of these residues from the soil may lead to significant environmental consequences that reduce the above mentioned functions [20]. In relation to the development of bioethanol LCAs based on biomass residues, therefore, it is important to consider the above mentioned competing uses or functionality as a reference to the proposed bioethanol system.

Biomass waste is lignocellulosic biomass generated in the plantation, in post-harvest processing or other activities which have no economic value or functional uses. In addition, it is available in excess and in need of treatment or disposal. Biomass wastes result from an activity of which the main product has already been attributed most of the burden. In practice, it is observed that biomass wastes were not attributed with any environmental burden from the upstream chain [19,23–25]. Although, in theory, how these wastes were generated need to be further studied. Moreover, its conversion into bioethanol can even be credited for avoiding the need for waste treatment chain.

3.2. System components of the bioethanol system

3.2.1. Agricultural chain

Important aspects of the agricultural chain in relation to LCA studies are land use, carbon sequestration, addition of agrochemical input, the effects of removing biomass residues from soil, and biomass transport to ethanol conversion facilities. Carbon sequestration, agrochemical input, and biomass removal are related to the land use aspect, but they are treated separately due to their specific relevance in the bioethanol system, as latter shown in the survey results.

With regard to the land use component, direct land use change (dLUC) occurs when new agricultural land for producing bioethanol feedstock displaces prior land use, for example the conversion of forest land into corn plantation [13], while indirect land use change (iLUC) can be illustrated as an increase in demand for forest log and forest residues in one place due to increased logging activities or deforestation in another place [9]. For the purpose of producing bioethanol feedstock, the latter authors suggested neither using carbon-rich land covers nor displacing an existing agricultural activity. In the case where these preferences cannot be realized, an iLUC may be induced to a certain extent and this indirect impact should be included. In this regard, some frameworks on indirect land use modeling have been proposed [26,27].

Energy crops are responsible for environmental burden in relation to the use of land area and water, provision of seeds, and agrochemical input such as fertilizers and pesticides needed to grow the plant. Cultivation of agricultural land does not only give benefits in terms of an increased carbon sequestration by the vegetation and soil microorganisms, but can also be a source for atmospheric GHGs, depending on the land use and management options [20]. These are emission of N_2O due to the application of nitrogen based fertilizer and organic decomposition, increased emissions of CH_4 due to a decreased rate of CH_4 oxidation, and increased emissions of CO_2 due to organic decomposition [28,29]. The same authors also stated that organic carbon is stored in three different pools: vegetation, litter, and soil. Soil carbon sequestration is enhanced when biomass residues are kept in the soil due to an increase in the biodiversity and activities of soil microorganisms [20]. The carbon sequestration of the energy crops is usually calculated as CO_2 uptake of the photosynthetic activity of the main vegetation.

Agrochemicals introduced into agricultural soil are mainly fertilizers to enhance designated plant growth and pesticides to minimize pest. The use of nitrogen-based fertilizer may increase the risk of eutrophication and acidification [28] when its application fails to consider migration possibility of the excess (unadsorbed) fertilizer into surface or ground water. A similar mechanism applies to the use of excess pesticides that increases potential impacts of toxicity to human or animals. Such impacts have been demonstrated by Bai et al. [30] who concluded that in a bioethanol system based on switchgrass, the agricultural chain is the main contributor to eutrophication, acidification, and toxicity.

Removal of biomass residues may lead to a decline of soil quality and agronomic productivity that further leads to a reduced carbon sequestration capacity of the soil [20]. The benefit of reduction of nitrogen-related emissions (N_2O and NO_x, emissions, NO_3^- leaching) due to biomass removal may be offset by reduction in carbon, nitrogen, and other nutrients of the soil [31]. The level of carbon reduction due to biomass removal is equal to the biogenic carbon of the biomass residues (fraction of the crop) removed from the soil. Soil with a low carbon level contributes to increased levels of GHG in the atmosphere; on the other hand, soils to which crop residues are returned tend to store more soil organic carbon (and nitrogen) than plots where residues are taken away [32]. In this regard, fertilizer supplement may be necessary to maintain the nutrient level of a healthy soil [21]. The nature of these effects however is not consistent from one place to another, depending on local conditions such as climate, soil type, and crop management [13]. Other important inventory items related to the biomass removal from soil are energy use for collection of the biomass [21]. For biomass residues generated from a post-harvest processing unit (non-agricultural soil), the consequences of its removal from the site should be considered by referring to its competing uses such as heat feedstock, animal feed, fiber, fertilizer, or compost. If the biomass is available in excess, it may also be treated as wastes with no burden attribution.

Biomass transport from the plantation to the bioethanol production plant is also an important aspect of the bioethanol system. The bioethanol production site is supposedly not too far away from the agricultural field, so that environmental burden due to transportation of the biomass feedstock is not really a problem. This consideration also applies to transportation activities at different chains within the life cycle. The sensitivity of different transport distances to the overall LCA outcomes has been demonstrated by Bai et al. [30]. Table A.1 shows that the range of distances for biomass transportation in the reviewed papers is between 20 and 180 km. Consideration of transportation distances is related to the potential energy yield of the feedstock relative to energy used for transportation. The manageable transportation distance also depends on water content of the biomass. It will control energy density and quality of the feedstock at the bioethanol production gate since 'wet' biomass will deteriorate faster during long-distance delivery. According to International Energy Agency (IEA-Bioenergy), maximum economic transport distance of biomass for bioenergy is limited to 100 km [33].

3.2.2. Bioethanol production chain

Lignocellulosic biomass conversion technologies are also the source of variation in the outcome of the overall impact assessment. The conversion of the biomass into bioethanol consists of several processing steps, such as pretreatment to remove lignin from the fiber matrix or hydrolysis of hemicelluloses to C5-sugar (pentose), hydrolysis of cellulose to produce C6-sugar (glucose), and fermentation to convert both sugars into bioethanol. Yeast is

conventionally used to convert glucose only, but recently some micro-organisms are known to be able to consume both C5- and C6-sugars, giving a higher bioethanol yield. Process configurations can be arranged as SHF (separate hydrolysis and fermentation), SSF (simultaneous saccharification and fermentation), SSCF (simultaneous saccharification and co-fermentation), or the most advance process CBP (consolidated bioprocess). These different process configurations reflect an increasing level of technology. Co-fermentation of C5- and C6-sugars and CBP process in particular will give a higher yield and require less energy input. However, these advanced processes are still in developing stages and classified as near-term and long-term technologies, depending on the maturity of the technology. The drawback of using such future technologies is that no validation can be made since no commercial processes yet exist. LCA analysis focused on the uncertainty aspects of the application of this emerging production technology has been studied thoroughly by Spatari et al. [14].

Cellulase enzyme used to hydrolyze cellulosic polymer into sugar monomer is known to be a dominant factor in the overall cost of bioethanol production. The production of this enzyme is expensive and energy intensive. It costs about $0.50 per gallon of cellulases from Novozymes [7]. Its coverage in the inventory of bioethanol system is influential on the overall outcome of the LCA studies. Another important feature in the bioethanol production chain is the distillation of fermentation broth at rather low (8%) ethanol concentration to produce 95% ethanol, and the following de-hydration process to bring the ethanol up to 99.5% purity. These processes obviously require large amount of energy to remove water, but the final impact on net-energy output would clearly depend on energy mixtures of each country. The same bioethanol system can end up with different LCA results due to energy variability by country.

3.2.3. Bioethanol use chain

Bioethanol use as transportation fuel refers to the combustion of the fuel mix (5%, 10%, 85% ethanol in gasoline) in a vehicle internal engine. Tail pipe emission in this case is the most important aspect to be considered since ethanol blending and pure gasoline will certainly produce different emissions. Up to 10% ethanol in the fuel blend can be used in a conventional vehicle, while an 85% ethanol fuel needs a modified engine (flexible fueled vehicle). According to Festel [34] and Balat et al. [35], the energy density of bioethanol (21.14 MJ/L) is around 33–34% less than that of gasoline (32 MJ/L). But the combustion efficiency of a fuel blend in terms of km distance traveled is determined also by the type of vehicles, type of roads, fuel composition, and the speed of the vehicle. High ethanol percentage in the fuel blend seems to be more helpful to clearly see the environmental performances of using bioethanol in comparison to conventional gasoline [30]. In this relation, 100% ethanol blend is also used in the study, but only as a reference for fuel use comparison (see Table 3).

3.3. Aspects of LCA methodology

3.3.1. Functional unit

According to ISO 14040 [10], the functional unit is defined as the quantification of the identified functions (performance characteristics) of the products. Its main role is to be used as a reference to quantitatively connect inputs and outputs of a life cycle inventory. In this way, LCA results of the same functional unit could be compared from one another, provided that the system boundary is also similar. Proper functional unit that reflects the reality well is very important in the LCA study since different choice of functional units from the same system may result in different outcomes [12]. In bioethanol systems, the functional unit can take many forms depending on specific conditions of the system which is formulated in goal and scope of an LCA study. There are two main concerns related to this parameter: which function to choose and what unit that reflects reality well. Typical functional units of a bioethanol system in the reviewed papers are input land area, volume or mass of input biomass, volume or mass of ethanol product, caloric value of ethanol product, and driving distance of a car. These choices of functional units are driven by the main questions or goals of the LCA study. For example, to compare the benefit of gasoline and bioethanol systems as transportation fuels will lead to a functional unit in terms of 1-km driving distance. A functional unit in the form of 1 MJ would be more appropriate to compare the best use of biomass as bioenergy (bioethanol, heat, or electricity). Therefore, it may be difficult to interpret results of different functional units. In the case that comparison is still to be made, van der Voet et al. [12] recommend to re-calculate two LCA studies of different functional units by first making their units the same. To be able to perform this procedure, the boundary of the compared systems should be well defined. As defined above, usually a functional unit refers to the characteristics of a product. However, in the case of biorefinary or parallel processes which result in multiple products, but with no clear criteria to choose the main product, an input reference flow is often used, such as in the case of Uihlein and Schebeck [37]. Detailed data are given in the following section (see Fig. 5).

3.3.2. Allocation methods

Allocation is a procedure to attribute environmental burden of multi-functional processes to their input or output flows of the products under study. With respect to second generation bio-fuel, specific problems that often appear are in relation to different types of feedstock that may give specific consequences to burden allocation. In relation to the above feedstock classification, we suggest the following allocation criteria. Processes related to the energy crops will receive most of the burden, mainly from the burden of growing the plant. In this regard, energy crops are treated as a main product in agricultural chain. In contrast, wastes are not attributed with any environmental burden; in fact, their conversion into bioethanol can be credited for avoiding the use of waste treatment chain. For biomass residues, the attribution of the burden is not straight forward as they will be treated as co-product or by-product. Referring to Clean Development Mechanisms, Singh et al. [11] defined co-products, by-products, and wastes according to their economic values. Co-products have similar revenues as the main-product, by-products have a much lower value than co-products, and wastes have no or even a negative value. Based on these definitions, theoretically, the weight of environmental burden attributed to biomass residues should be between energy crop (fully attributed) and waste (no attribution), depending on the degree of economic values or functional uses (soil conditioner, compost, heat feedstock) of the biomass residues. However, we still need further elaboration as to how this kind of approach will be specifically applied in relation to different feedstock classification for bioethanol systems. The problem of allocation methods is more pronounced in the second generation bioethanol than the first generation bioethanol [12,22]. This unique problem of allocation is obviously driven by different types of feedstock generated in the agricultural chain.

ISO 14040 suggests the system expansion in the first place, but allows an allocation approach to deal with co-products as well. This points to obvious methodological choices. Deviating from ISO, the EU Directives on biofuel suggest allocation based on energy content in preference to the system expansion [12].

We deliberately elaborate more on the allocation approach to demonstrate how these three different feedstocks should be treated, although it may not be as important in the system expansion approach.

3.3.3. Impact categories

Impact categories of concern for biofuel LCAs are mainly whether or not the systems give surplus energy, followed by concern on global warming. Besides these two, there are many other categories of high relevance, although these have not been considered in sufficient detail. These include land and water use in relation to increasing pressure of growing population [38], toxicity and biodiversity [9]. In this relation the latter authors emphasize that producing biofuel from land other than degraded land is likely to increase GHG emission, damage biodiversity, and affect food security. Agriculture for the feedstock generation is not the only part of the chains that required water. Koh and Ghazoul [39] reported an estimate that bioethanol production required 4 gallons of water per gallon bioethanol produced, while a fuel oil refinery only needs 1.5 gallons of water per gallon fuel oil produced. The importance of other relevant impact categories in relation to bioethanol system, such as eutrophication and acidification, has been described in Section 3.2.1.

4. Results and discussion

4.1. Feedstock classification

Based on our feedstock classification described in Section 3.1 and data in the tables of Appendix A, energy crops include switchgrass, *Brassica carinata*, poplar, and wood log; biomass residues include alfalfa stem, corn stover, straw, bagasse, flax shives, wood residues, hemp hurd, and oil palm biomass residues; and biomass wastes include recycled paper and municipal solid wastes. We included a biomass feedstock as energy crops if it is the main product and used most parts of the plant for example as in the case of wood log [6,25], while wood residues as biomass residues [4,24]. Detail on the feedstock type of the reviewed papers can be seen in Fig. 2. It is clearly seen that the most studied feedstocks are biomass residues (19 studies), followed by energy crops (8 studies), and biomass wastes (4 studies).

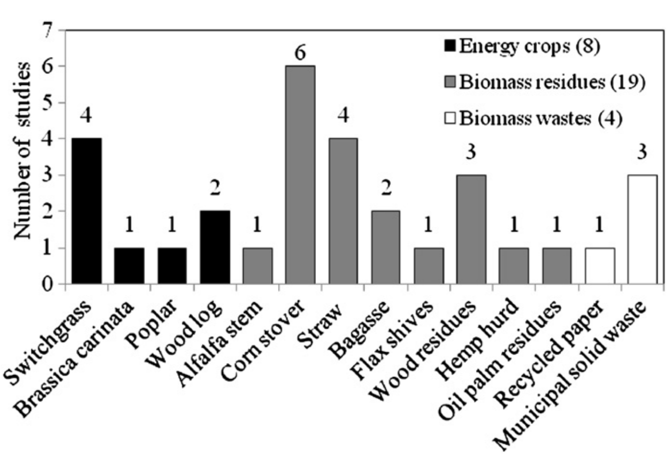

Fig. 2. Types of lignocellulosic biomass feedstock in the LCA studies of the reviewed papers. Numbers within bracket in the series legend denote total number of studies on each feedstock classification.

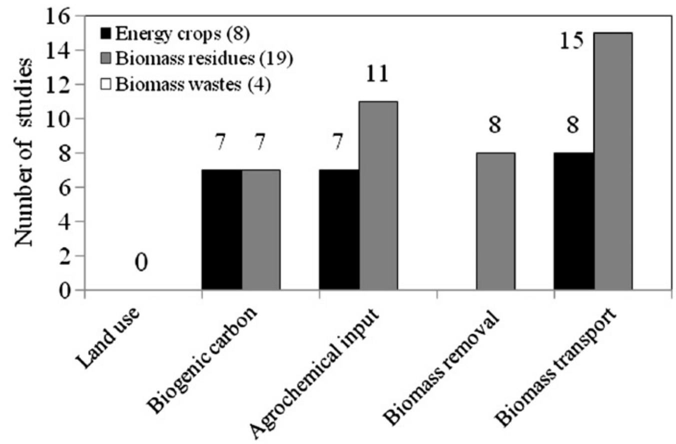

Fig. 3. System components of the agricultural chain included in the LCA studies of the reviewed papers. Numbers within bracket in the series legend denote total number of studies on each feedstock classification.

4.2. Agricultural chain

Fig. 3 shows that no study included land-use in the inventory calculation, both at the transformation or occupation levels [40]. A possible reason for this is that the energy crops are mainly grown on marginal or degraded soils. Such land is believed not to compete with other utilization such as for food, feed or fiber. Therefore, its environmental impact is minimal; in fact, utilization of these lands for cropping can even increase the capacity of carbon sequestration [16].

In Fig. 3, LCA studies that considered carbon sequestration are grouped as biogenic carbon on the horizontal axis. A rather high percentage (88%) of the LCA studies based on energy crops includes this aspect in their system boundary, while for biomass residues, only 37% of the studies considered carbon sequestration. Below, data in Table 3 will demonstrate that the aspect of biogenic carbon hold a very important feature in the agricultural chain of the overall bioethanol system.

A large number of studies based on energy crops (88%) and biomass residues (58%) included agrochemical input in the analysis. These agrochemical inputs are in the form of fertilizers and pesticides for energy crops and fertilizer as nutrient replacement in the case of biomass residues. The fertilizer is added only when the rate of biomass removal interferes with its function to maintain top soil quality. To avoid such environmental burden, the removal of biomass residues therefore is done only at a rate (percentage) that does not bring any consequences to the reference systems. Data in Fig. 3 shows that only 42% of the studies based on biomass residues considered the consequences of biomass removal. This category includes those that removed only the surplus biomass in the amount that does not affect the environment and those that compensated the biomass removal by inorganic fertilizer as nutrient replacement. The rest of the studies (58%) did not mention or might not consider biogenic carbon in the inventory. No environmental burden attributed to the biomass wastes as a feedstock category means that these studies excluded the agricultural chain from the life cycle inventory. The aspect of biomass transport is self-explained and the impacts will depend partly on the distance between agricultural site and the bioethanol processing facilities. In this case the distances are between 20 km and 180 km. A larger distance means that a higher amount of fuel is needed and more pollution from the tail pipe is emitted.

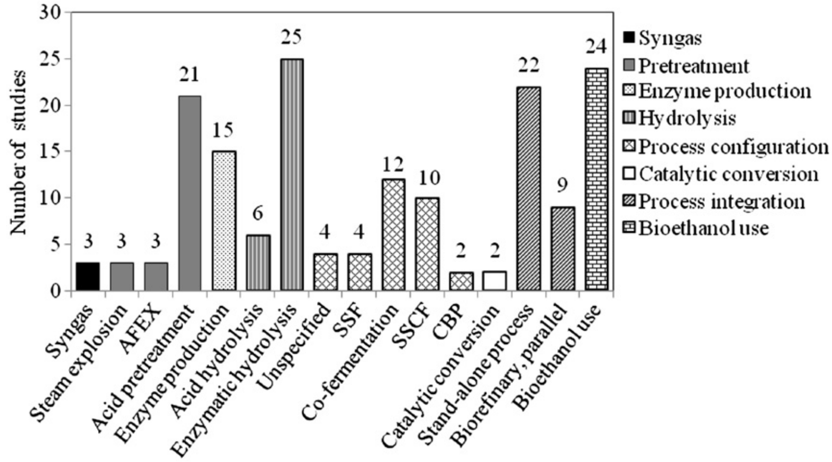

Fig. 4. System components of the bioethanol production chain included in the LCA studies of the reviewed papers. AFEX = ammonia fiber explosion, SSF = simultaneous saccharification and fermentation, SSCF = simultaneous saccharification and co-fermentation, CBP = consolidated bioprocess.

The above conditions show a very high variation in the practice of defining the system boundary in the agricultural chain, particularly with respect to land-use, biogenic carbon, agrochemical input, biomass removal consequences, and biomass transport. These facts bring a strong message that a clearer guidance to properly include or exclude certain parts of system components based on feedstock classification is needed. The main motivation is in order to be able to allocate environmental burden accordingly.

4.3. Bioethanol production and use chains

Fig. 4 shows important system components in the bioethanol production and use chains that include pretreatment, enzyme production, hydrolysis, fermentation, and bioethanol use. The pretreatment technology used in the bioethanol production chain is dominated by acid pretreatment (21 studies), followed by steam explosion (3 studies), and AFEX process (3 studies). The conversion of cellulose into sugar is dominated by enzymatic hydrolysis (25 studies), while only 6 studies dealt with acid hydrolysis. Although quite some studies included enzymatic hydrolysis, only 15 studies incorporated enzyme production in their inventory analysis.

With regard to the process configuration in terms of hydrolysis and fermentation processes, none of the studies was based on a relatively simple technology such as SHF. Most of them used advanced technology involving co-fermentation of C5- and C6-sugars (12 studies), SSCF (10 studies), and CBP (2 studies). The syngas process and the following catalytic conversion or fermentation was found as a minor technological route in the LCA studies, possibly because this technology is less established and therefore less data are available as compared to the fermentation route.

Fig. 4 shows that only 88% of the studies based on fermentation reported their specific process configurations, 75% of which used advanced processes such as co-fermentation, SSCF, and CBP. In this review, we differentiate co-fermentation from SSCF, and refer to the first one if the authors mentioned co-fermentation only without detail explanation on how the hydrolysis was done. The above trend has been previously reported by Sheehan et al. [41] who stated that most of the LCA studies are based on projected future technology that is not yet commercially proven. In this regard, there is a risk to underestimate the real impacts of the current production technology (SHF or SSF of glucose only) which is typically lower in bioethanol yield. Fluctuation in the LCA results due to different technological levels has been demonstrated based on simulation of different technological scenarios:

Table 1
Data on sugar recovery and fermentation efficiency in bioethanol production that were referred to by most of the reviewed papers.

Authors	Sugar recovery after pre-treatment and hydrolysis (%)		Fermentation efficiency of different sugars (%)		Cited by
	Glucose	Xylose	Glucose	Xylose	
Hamelinck et al. [8]	90	85	92.5	85	[28,29]
Sheehan et al. [41]	63.5	67.5	95	90.2	[21]
Wooley et al. [44][a]	80	85	92	85	[4,25]
Aden et al. [45][b]	90	90	95	85	[5,22,24,49,52–54]

[a] Near term, best of industry, page 60.
[b] Process parameters, Appendix E.

near-term (SSCF technology in 2010) and mid-term (CBP technology in 2020) [14]. Therefore, sensitivity analysis at different levels of technology becomes necessary, so that the conclusion can be understood within the context of the study.

With regard to process integration, 22 studies covered the inventory at the level of bioethanol production only (stand-alone process), isolated from the other system processes. Meanwhile, 9 other studies expanded the inventory of the bioethanol systems to include their respective biorefinery systems or related processes. The examples to these are the inclusion of biodiesel or sugarcane production system in the system boundary in case where palm oil biomass [42] or bagasse residues [43] were used as feedstocks, respectively.

The potential amount of sugar available for fermentation is governed by the cellulose and hemicellulose content of the biomass feedstocks, and by the effectiveness of the pretreatment and hydrolysis steps. The higher cellulose and hemicelluloses content of a biomass, the higher sugar yield can be achieved as long as the pretreatment and hydrolysis can be done easily. In turn, these resulting sugars will be fermented to yield the final product, bioethanol. Table 1 illustrates variation in sugar recovery and fermentation efficiency that were used by most of the reviewed papers in developing a LCA of bioethanol system, reflecting advance level of technology. These data are based on the work done directly [41,44,45] or indirectly [8] at the National Renewable Energy Laboratory (NREL) of the USA. In addition, Table 2 shows the gaps between the values observed at the bench scale results (in 2004) and those used in the LCA study based on

Table 2
Sugar recovery and fermentation efficiency at bench-scale and projection used in the LCA study [41].

Conversion reaction	Yield (%)					
	Pretreatment		Hydrolysis		Fermentation	
	Observed bench scale[a]	Future projection used in LCA	Observed bench scale	Future projection used in LCA	Observed bench scale	Future projection used in LCA
Xylan to xylose	67.5	90	–	–	–	–
Arabinan to arabinose	67.5	90	–	–	–	–
Mannan to mannose	67.5	90	–	–	–	–
Galactan to galactose	67.5	90	–	–	–	–
Cellulose to glucose	–	–	63.5	90		
Xylose to ethanol	–	–	–	–	90.2	[b]
Arabinose to ethanol	–	–	–	–	0	85
Mannose to ethanol	–	–	–	–	0	85
Galactose to ethanol	–	–	–	–	0	85
Glucose to ethanol	–	–	–	–	95	95

[a] Observed bench scale data refers to the year of 2004 [41].
[b] The original paper notes a lower value (85%) than that of the observed bench scale.

future projections [41]. The data spread is quite large, between 63.5% and 90% for sugar recovery, and between 0% and 85% for fermentation efficiency of arabinose, mannose, and galactose. It is therefore important to justify clearly the choices of assumed values for process parameters at the pretreatment, hydrolysis, and fermentation stages. These different process scenarios in terms of sugar recovery and fermentation efficiency, at the end, will bring consequences to different amount of required energy input and yield of bioethanol as the final product.

4.4. Aspects of LCA methodology

Fig. 5 shows that the bioethanol system in most cases comprises a cradle to grave boundary by including bioethanol-use as transportation biofuel (24 studies), while only in 7 studies the inventory up to the gate of bioethanol production chain was taken into account.

The functional units of the reviewed papers are quite diverse. They are based on land area use for certain period (2 studies), volume or mass of input biomass feedstock (8 studies), volume or mass of bioethanol product (6 studies), caloric value of bioethanol product (8 studies), and driving distance of ethanol blends as transportation biofuel (10 studies).

Likewise, the allocation methods of the reviewed papers are quite varied. They are based on system expansion (1 study), substitution of avoided burden (15 studies), mass partitioning (7 studies), energy partitioning (4 studies), and economic partitioning (3 studies). The remaining studies either do not mention allocation (6) or consider allocation (4) in their studies. In this paper, we deliberately differentiate between system expansion and substitution with the aim to clearly show different kinds of system expansions really applied by LCA studies in practice. Allocation based on substitution of avoided burden was the most popular allocation method (50%), followed by partition methods (mass, energy, economic based, 47% in total). The allocation method based on system expansion is only 3%; it involves a rather tedious calculation since a lot of information is needed. It seems that the preference to use substitution methods is motivated mainly by data availability and practical considerations. This conclusion is similar to general biofuel LCAs based on more heterogeneous feedstocks [12].

Global warming is the most studied impact category (29 studies) followed by net energy output (18 studies), acidification and eutrophication (15 studies each). Although the bioethanol systems reviewed use rather diverse approaches in terms of LCA

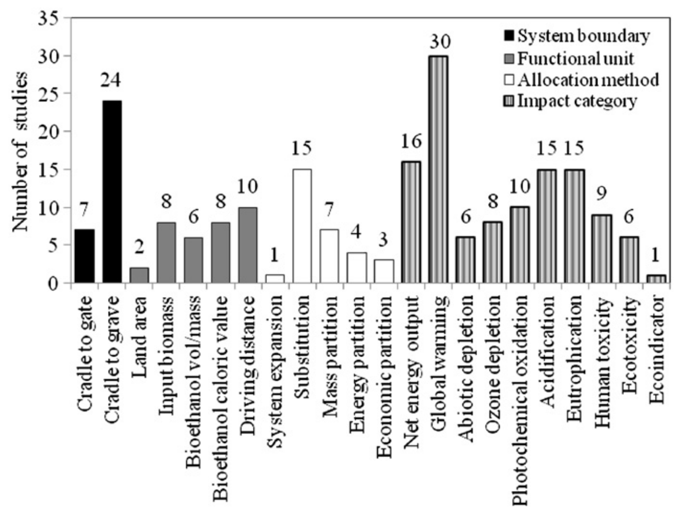

Fig. 5. Different aspects of LCA methodology in the reviewed papers.

methodology, system definition, and level of technology, the conclusion to favor the second generation bioethanol is quite robust for net energy output and global warming. Not all studies declare in detail the methods used to assess the impact of global warming. Only 7 studies mentioned a time horizon of 100 years, and 4 studies explicitly listed the equivalency factors relative to CO_2, i.e. between 21 and 25 for CH_4, and between 296 and 310 for N_2O.

We conjecture, however, that environmental sustainability based on a more complete set of impact categories may give different outcomes. The extent to which they really do so is not verifiable since most of the studies are based on different system boundaries and consider different impact categories. Despite this, bioethanol systems that include productive-land use in the case of energy crops or coal as energy sources are believed to be consistently unsustainable. Relevant impact categories which have not been dealt with by many of these LCA studies are eutrophication, acidification, toxicity, land use, biodiversity, and water use. With regard to the last four categories, they are often not included since the required parameters are not well developed in the LCA methodology and consequently not readily available in the commercial LCA software. Ecoindicator is a single-score impact category based on end-point assessment [46].

4.5. Impact assessment results with reference to conventional fossil oil system

Referring to Fig. 6, the second generation bioethanol provides a more unified direction in favor of its implementation based on two major criteria: net energy output and global warming. This convergence of LCA results cannot be observed in a study with a broader spectrum of feedstocks [12,15,16]. The impact assessment results revealed that 14 studies concluded a positive net-energy output (between 64% and 86% compared to the gasoline system), while only 2 studies [42,43] reported the opposite. Similarly, 28 studies reported an increase in GHG saving (between 11% and 145% compared to the gasoline system), while only 3 studies [22,42,43] reported worse cases. We noticed that the divergence took place only in the case of biomass residues. It may suggest that the system components of this type of feedstock are rather difficult to define, as compared to energy crops or biomass wastes. In addition, there are also other technical reasons that explain this divergence as illustrated in the following.

Luo et al. [22] revealed that using corn stover as the feedstock and fossil oil as the reference, the impact scores on global warming are contradicting one another when using different allocation methods. Partitioning based on physical properties (mass or energy content) resulted in smaller global warming, while the same system emitted more GHG when using economic allocation. The partitioning ratios between corn grain and corn stover based on physical properties and economic value are so big that the ratio shifted from 1.7 to 7.5. The ratio based on physical

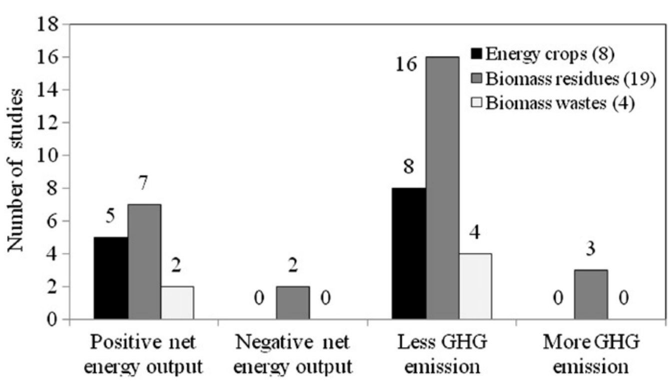

Fig. 6. Summary of impact assessment results for net energy output and global warming from the LCA studies of the reviewed papers. Numbers within bracket in the series legend denote total number of studies on each feedstock classification.

allocation is rather stable, while that based on economic value will vary following market forces that depend on time and location. In this relation, it would be nice if the prices of the compared products are fixed, but in fact price ratios may be so volatile that their usefulness is limited in practice. On the other hand, choosing a physical basis for allocating burden does not always describe the reality well [47].

Lim and Lee [42] reported that the inclusion of bioethanol production parallel to a biodiesel system will decrease the environmental performances in terms of output energy and global warming. They assumed a very low bioethanol yield based on 26.5% cellulosic materials contained in the palm oil biomass residues. However, a sensitivity analysis with a higher bioethanol yield (cellulosic materials above 60%) reveals opposite results, a lower energy input and GHG emission, meaning a better environmental performance. Referring to the provided composition of cellulose and hemicellulose of the EFB (empty fruit bunch) in this paper [42], it seems that the low cellulosic content (26.5%) refers to the use of C6-sugar originating from cellulose only, while the high cellulosic content (60%) suggests co-fermentation of both C5- and C6-sugars originating from cellulose (26.5%) and hemicelluloses (34.4%), respectively. This analysis demonstrates that a difference in technology level of bioethanol conversion (fermentation of C6-sugar only and co-fermentation) also plays an important role in determining the outcome of the LCAs.

Melamu and von Blottnitz [43] reported that the conversion of sugarcane bagasse into bioethanol in a sugar milling industry will give negative results for net energy output and global warming. They refer to the baseline case, a sugar industry with self-sufficient energy system by burning the bagasse as a heat feedstock to generate boiler steam. In the proposed bioethanol scenario, the heat generated from bagasse is replaced by coal, a typical energy source available in the area (South Africa). Comparison between these two energy scenarios in a sugar industry indicated that coal becomes the dominant contributor to global warming, governing the bad performance of the overall system.

Pimentel and Patzek [36] worked on an energy analysis of bioethanol production based on corn, switchgrass, and wood, and found negative energy outputs as high as 29%, 50%, and 57% respectively. Since this is not an LCA study, the data are not included in Figs. 2–6, but discussed here because of its relevance. These negative energy outputs, however, seem to be related in different ways in treating co-products between energy analysis and LCA studies. For example, in the case of the corn system, the authors did not incorporate co-products (corn stover) in the calculation as a typical approach in an LCA study. An attempt to

Table 3
Contribution analysis on global warming at different ethanol percentages.

Feedstock	% Ethanol in a fuel blend	GHG emission intensity				References
		Agricultural chain		Production of fuel blends[a]	Use of fuel blends	
		CO_2	N_2O			
Brassica carinata	10	– –	+	++	++++++	[5]
Brassica carinata	85	– – – – – – –	+	+++	++	[5]
Switchgrass	10	– –	+	++	++++++	[30]
Switchgrass	100	– – – – – – –	+	+++	++	[30]
Switchgrass	100	– – – – – – –	+	+++	++	[21]
Corn stover	100	– – – – – – –	+	+++	++	[21]
Corn stover[b]	100	– – – –	+	++++++	+++	[22]
Flax shives	100	– – – – – – –	+	+++	++	[49]

+ Denotes GHG emission; – denotes GHG saving; number of + or – indicates relative emission or saving intensity, respectively, interpreted from the figures of the respective papers; more + than – means net GHG emission; more – than + means net GHG saving.

[a] Environmental burden for the production of fuel blends include both for the gasoline and bioethanol fractions.

[b] Based on economic allocation.

recalculate Pimentel's energy assessment by considering also the co-products in the agricultural (feedstock) and biorefinery (energy product) chains has been made [48]. It was found that the net energy output of the overall feedstock system (corn grain and corn stover) shifted from negative (-5.8 MJ/L) to positive ($+22$ MJ/L) values. This case nicely demonstrates the consequence of removing some of the relevant components from the system, leading to contradictory results.

Up to this point, we have shown that many LCA studies of cellulosic bioethanol system have not consistently included important system components, particularly in the agricultural chain where the type of feedstocks (energy crops, biomass residues, and biomass wastes) varies and where different levels of bioethanol production technology (current and future scenarios) are adopted. In this regard, there is a need to develop common rules for applying LCA to agricultural systems, so as to increase the comparability of studies based on the identified system components. If the difference is large, the environmental impact of certain parts of life cycle chain may fluctuate depending on the coverage of system components and the technology levels at that specific part. In such cases, a contribution analysis is therefore necessary. It is a method to sort out hot spots, the parts of the system components in a life cycle that make up most of the environmental burden or impact. The changes of the hot spot can be seen as a shift in dominant contributors (agricultural chain, production of fuel blends, or use of fuel blends) relative to the overall environmental burden, as illustrated in the following.

The data in Table 3 demonstrates that agricultural chains of energy crops and biomass residues are consistently found as the dominating factor in term of GHG saving to determine the overall impact on global warming at high ethanol percentage ($\geq 85\%$). On the other hand, the use of fuel blends dominated by GHG emission controls the direction of overall impact at low ethanol percentage (10%). There are two important aspects in the agricultural chain related to the impact on global warming pointing at different directions: carbon sequestration and emission of nitrous oxide and methane. In the case of high ethanol percentage, the carbon sequestration quantified as carbon uptake from the atmosphere offsets the emission from all parts of the life cycle chains (N_2O and CH_4 emissions, production of fuel blend, and use of fuel blend). When the ethanol fraction in the fuel blend is reduced to only 10%, such as in the case of *Brassica carinata* and switchgrass, the capacity of carbon sequestration decreases significantly, leading to a net GHG emission. Table 3 also shows that the hotspots of the life cycle chain shift from the use of fuel at low ethanol percentage to the fuel production at high ethanol percentage.

The above analysis shows the importance of indicating the blending percentage of the ethanol in the fuel blends when comparing environmental performance of a bioethanol system with reference to conventional fossil oil. It is also recommended to use a high ethanol percentage (high gasoline displacement) in the LCA study, so that its effect on the overall GHG emission relative to the reference system can be seen even clearer. One exception at high ethanol percentage is the corn stover case of Luo et al. [22] in which the dominant burden was found to be the bioethanol production chain. As discussed previously, this appears to be influenced by the choice of economic allocation in this multi-product system.

5. Conclusions

We suggest that a classification of lignocellulosic biomass can be used as a guidance to include or exclude certain parts of system components and to attribute environmental burden accordingly. With reference to the feedstock generating history, energy crops are treated as a main product in the agricultural chain and receive most of the burden of growing the plantation. In practice, biomass wastes are not attributed with any environmental burden. Theoretically, however, how these wastes were generated need to be considered. In fact, waste conversion into bioethanol can be credited for avoiding the need for waste treatment chain. Biomass residues can be treated as co- or by-products, and the share of environmental burden attributed to them is between energy crops (fully attributed) and biomass wastes (no attribution), depending on their economic values or functional uses.

Although the bioethanol studies reviewed use rather varied approaches in terms of LCA methodology, definition of bioethanol system, and level of technology, the conclusion to favor the second generation bioethanol is quite robust at least for the two most studied impact categories, net energy output and global warming. For the latter category, carbon sequestration at the biomass generation stage can even consistently offset the GHG emissions from all parts of the life cycle chains at high ethanol percentage ($\geq 85\%$). Studies based on a more complete set of impact categories such as eutrophication, acidification and toxicity are likely to lead to different outcomes, particularly when productive land or coal is included in the bioethanol system. Other relevant impact categories which have not been sufficiently dealt with are land use, biodiversity, and water use.

In the agricultural part of the chain, the aspect of biogenic carbon and agrochemical input for energy crops and biomass residues, and the effect of removal of the latter from agricultural soil have not been treated consistently.

Most of the LCA studies use advanced process configurations (such as SSCF and CBP) that are still in developing stages and no existing commercial scale can be referred to for validation. In this regard, there is a risk of under-estimating the real impacts of the current production technology which are typically lower in bioethanol yield and consumed more energy. Sensitivity analysis is necessary, so that the conclusion can be understood within the context of a specific technology level.

The choice of allocation methods has a strong influence on the overall LCA results. This may lead to contradictory outcomes, particularly when economic value (which depends on market forces) is used as opposed to physical properties (mass or energy content) which are relatively more stable. Allocation based on substitution of avoided burden seems to be the most popular allocation method in practice, followed by partition based on mass, energy, and economic values. The preference to use such allocation methods is motivated mainly by practical considerations and data availability.

Overall, we conclude that a clearer guidance in terms of best practice for LCA of second generation bioethanol based on lignocellulosic biomass is needed, with a focus on methodological aspects (functional unit, allocation, system boundaries, impacts included) as well as data aspects (technological level, feedstock specification).

Acknowledgment

Financial support from NFP-Nuffic the Netherlands for EIW is gratefully acknowledged. Appreciation is also given to Research Center for Chemistry, Indonesian Institute of Sciences (LIPI) for giving an opportunity for EIW to pursue Ph.D. study at Leiden University, the Netherlands. We would like to thank Patrik Henriksson of CML, Leiden University, the Netherlands and Alessandra Zamagni of ENEA, Italy for useful comments on the manuscript.

Appendix A. Overview of the studies

This section contains detailed information of data presented in Figs. 2–6. The references to the survey results can be found in Tables A.1–A.4

Table A.1
System components of the agricultural chain.

Class	References	Feedstock[a]	Biogenic carbon[b]	Agrochemical input[c]	Consideration on the effect of biomass residues removal[d]	Biomass transport[e]
Energy crops	[30]	Switchgrass	C-sequestration	Fertilizer, herbicide	Not applicable	20 km
	[5]	*Brassica carinata*	C-sequestration	Fertilizer, pesticide		25 km
	[25]	Wood log	Excluded	Excluded		Included
	[6]	Soft wood	C-sequestration	Fertilizer		Included
	[14]	Switchgrass	C-sequestration	Fertilizer, herbicide		65 km
	[21]	Switchgrass	C-sequestration	Fertilizer, herbicide		90 km
	[28]	Switchgrass	C-sequestration	Fertilizer, herbicide		120 km
	[53]	Poplar	C-sequestration	Fertilizer, pesticide		25 km
Biomass residues	[50]	Bagasse	–	Fertilizer	–	50 km
	[4]	Wood residues	–	–	Surplus residues only	50–120 km
	[49]	Flax shives	C-sequestration	Fertilizer, pesticide	–	180 km
	[22]	Corn stover	C-sequestration	Fertilizer, pesticide	60% Removal	56 km
	[51]	Straw	Excluded	–	Assumed no effect	Included
	[51]	Corn stover	Excluded	–	Assumed no effect	Included
	[6]	Straw	Excluded	Nutrient replacement	Considered	Included
	[14]	Corn stover	C-sequestration	Nutrient replacement	50% Removal	65 km
	[21]	Corn stover	C-sequestration	Nutrient replacement	62% Removal	90 km
	[24]	Hard wood residues	–	–	–	–
	[24]	Soft wood residues	–	–	–	–
	[24]	Corn stover	–	–	–	–
	[37]	Straw	–	–	–	100 km
	[29]	Corn stover	–	Nutrient replacement	Considered	120 km
	[29]	Wheat straw	–	Nutrient replacement	Considered	120 km
	[42]	Oil palm residues	C-sequestration	Fertilizer, pesticide	Considered	100 km
	[43]	Bagasse	–	–	–	–
	[52]	Hemp hurd	C-sequestration	Fertilizer	–	Included
	[54]	Alfalfa stem	C-sequestration	Fertilizer, pesticide	–	100 km
Biomass wastes	[23]	Biodegradable MSW	Excluded	Excluded	Not applicable	Excluded
	[25]	Recycled paper	Excluded	Excluded		Included
	[19]	Biodegradable MSW	Excluded	Excluded		Excluded
	[24]	Biodegradable MSW	Excluded	Excluded		–

MSW = municipal solid waste, – = not mentioned. No land-use aspect is considered in the agricultural chain.

[a] Wood log [6,25] as the main biomass product is treated as an energy crop since most parts of the crop are used as feedstock, while wood residues [4,24] are classified as biomass residues. *Brassica carinata* is also treated as an energy crop, and assumed to yield only biomass, not oil seeds [5]. Alfalfa stem (50% of the biomass) is categorized as biomass residues since the main product is the leaf used as forage [54]. Flax shives are woody parts of the stems (about 25–30%) that are left over from fiber processing [49]. The mass ratio between corn grain and corn stover is 1:1 [22].

[b] Biogenic carbon in the case of energy crops is CO_2-sequestered during the plant growth, and in the case of biomass residues as carbon sequestered in the biomass fraction removed from the soil.

[c] Fertilizer is added for energy crops to enhance the plant growth, for biomass residues to replace nutrient removed from the soil.

[d] Whether or not the effect of biomass residues removal on soil quality (soil organic matter, soil biota, soil carbon sequestration, soil structure) is considered.

[e] Biomass transport from the plantation to bioethanol production plant.

Table A.2
System components of the bioethanol production and use chains.

Class	References	Feedstock	Pretreatment[a]	Enzyme production	Hydrolysis	Process configuration[b]	Process integration	Bioethanol use[c]
Energy crops	[30]	Switchgrass	AFEX	Included	Enzyme	SSCF	Stand alone	FFV: E10, E85
	[5]	*Brassica carinata*	Acid	Included	Enzyme	Co-fermentation [45]	Stand alone	FFV: E10, E85
	[25]	Wood log	Acid	Included	Enzyme	SSCF [44]	Stand alone	Excluded
	[6]	Soft wood	Acid	Included	Acid, enzyme	SSF [56]	Stand alone	Excluded
	[14]	Switchgrass	Acid, AFEX	Included	Enzyme	SSCF, CBP	Stand alone	Excluded
	[21]	Switchgrass	Acid	Included	Enzyme	Co-fermentation [41]	Stand alone	FFV: E85
	[28]	Switchgrass	Steam explosion	–	Enzyme	SSCF [8]	Biorefinary	Car: 2.45 MJ/km
	[53]	Poplar	Acid	Included	Enzyme	Co-fermentation [45]	Stand alone	FFV: E10, E85
Biomass residues	[50]	Bagasse	Acid	Excluded	Acid	Co-fermentation [55]	Parallel, sugar production	Included
	[4]	Wood residues	Acid Syngas	–	Enzyme	SSCF [44] Catalytic conversion	Stand alone	FFV: E85

Table A.2 (*continued*)

	[49]	Flax shives	Acid	Included	Enzyme	Co-fermentation [45]	Stand alone	FFV: E10, E85
	[22]	Corn stover	Acid	Included	Enzyme	Co-fermentation [45]	Stand alone	Car: E10 E85
	[51]	Straw	–	–	Enzyme	Fermentation	Stand alone	Included
	[51]	Corn stover	–	–	Enzyme	Fermentation	Stand alone	Included
	[6]	Straw	Acid	Included	Acid, enzyme	SSF [56]	Stand alone	Excluded
	[14]	Corn stover	Acid, AFEX	Included	Enzyme	SSCF, CBP	Stand alone	Excluded
	[21]	Corn stover	Acid	Included	Enzyme	Co-fermentation [41]	Stand alone	FFV: E85
	[24]	Hard wood residues	Acid	–	Enzyme	Co-fermentation [45]	Stand alone	FFV: E85
	[24]	Soft wood residues	Syngas			Catalytic conversion [57]	Stand alone	FFV: E85
	[24]	Corn stover	Acid	–	Enzyme	Co-fermentation [45]	Stand alone	FFV: E85
	[37]	Straw	Acid	Excluded	Acid	Co-fermentation[a][58]	Biorefinary	Car: E5
	[29]	Corn stover	Steam explosion	–	Enzyme	SSCF [8]	Biorefinary	Car: 2.45 MJ/km
	[29]	Wheat straw	Steam explosion	–	Enzyme	SSCF [8]	Biorefinary	Car: 2.45 MJ/km
	[42]	Oil palm residues	Acid	–	Enzyme	Fermentation	Parallel, biodiesel production	Car: E10
	[43]	Sugarcane bagasse	Acid	–	Enzyme	SSCF [59]	Parallel, sugar production	Excluded
	[52]	Hemp hurd	Acid	Included	Enzyme	Co-fermentation [45]	Stand alone	FFV: E10, E85
	[54]	Alfalfa stem	Acid	Included	Enzyme	Co-fermentation [45]	Stand alone	FFV: E10, E85
Biomass wastes	[23]	Biodegradable MSW	–	–	Acid	SSF [60]	Parallel, waste treatment	LDV: E85
	[25]	Recycled paper	Acid	Included	Enzyme	SSCF [44]	Stand alone	Excluded
	[19]	Biodegradable MSW	Syngas			Fermentation	Parallel, waste treatment	LGV
	[24]	Biodegradable MSW	–	–	Acid	SSF [60]	Stand alone	FFV: E85

MSW = municipal solid waste, – = not mentioned.

Table A.3
Aspects of LCA methodology.

Class	References	Feedstock	System boundary[a]	Functional unit	Allocation method	Impact category[b]
Energy crops	[30]	Switchgrass	Well to wheels	1 km Driving	Energy, economy	GW, AD, OD, PO, A, E, HT, ET
	[5]	*Brassica carinata*	Cradle to grave	1 km Driving, 1 kg ethanol	No allocation	GW, PO, A, E
	[25]	Wood log	Cradle to gate	83 T Biomass/h	No allocation	GW, OD, A, E, HT
	[6]	Soft wood	Cradle to gate	1 GJ Ethanol	Energy, substitution	GW
	[14]	Switchgrass	Cradle to gate	1 L Ethanol	Substitution	GW, Air pollutant
	[21]	Switchgrass	Cradle to grave	1 km Driving	Mass, substitution	GW, Air pollutant
	[28]	Switchgrass	Cradle to grave	477 kT Biomass/year	–	GW, AD, OD, PO, A, E, HT, ET
	[53]	Poplar	Cradle to grave	1 km Driving	Mass	GW, PO, A, E
Biomass residues	[50]	Bagasse	Cradle to grave	Sugar/Ha year	Substitution	GW, AD, A, E, HT, ET
	[4]	Wood residues	Well to wheels	1 km Driving	–	GW, A, E, HT
	[49]	Flax shives	Cradle to grave	1 km Driving	Mass, economy	GW, OD, PO, A, E
	[22]	Corn stover	Well to wheels	1 km Driving	Economy, mass, energy, system expansion	GW, AD, OD, PO, A, E, HT, ET
	[51]	Straw	Well to wheels	1 L Ethanol	Substitution	GW
	[51]	Corn stover	Well to wheels	1 L Ethanol	Substitution	GW
	[6]	Straw	Cradle to gate	1 GJ Ethanol	Energy, substitution	GW
	[14]	Corn stover	Cradle to gate	1 L Ethanol	Substitution	GW, Air pollutant
	[21]	Corn stover	Cradle to grave	1 km Driving	Mass, substitution	GW, Air pollutant
	[24]	Hard wood residues	Well to wheels	1 MJ Fuel	Substitution	GW
	[24]	Soft wood residues	Well to wheels	1 MJ Fuel	Substitution	GW
	[24]	Corn stover	Well to wheels	1 MJ Fuel	Substitution	GW
	[37]	Straw	Cradle to grave	1 T Straw	Substitution	EcoIndicator
	[29]	Corn stover	Cradle to grave	477 kT Biomass/year	–	GW, AD, OD, PO, A, E, HT, ET
	[29]	Wheat straw	Cradle to grave	477 kT Biomass/year	–	GW, AD, OD, PO, A, E, HT, ET
	[42]	Oil palm residues	Seed to wheels	1 Ha Land/100 year	Substitution	GW
	[43]	Sugarcane bagasse	Gradle to gate	1 MJ Ethanol	–	GW, A, E
	[52]	Hemp hurd	Cradle to grave	1 km Driving	Mass	GW, PO, A, E
	[54]	Alfalfa stem	Cradle to grave	1 km Driving	Mass	GW, PO, A, E
Biomass wastes	[23]	Biodegradable MSW	Well to wheels	1 kg Ethanol,24 MT MSW/h	No allocation	GW, Air Pollutant
	[25]	Recycled paper	Cradle to gate	83 T Biomass/h	No allocation	GW, OD, A, E, HT
	[19]	Biodegradable MSW	Cradle to grave	1 MJ Ethanol,190,000 T MSW/year	–	GW
	[24]	Biodegradable MSW	Well to wheels	1 MJ Fuel	Substitution	GW

MSW = municipal solid waste, – = not mentioned.

[a] For simplicity, system boundaries presented in Fig. 5 and Table A.3 do not differentiate among 'cradle to grave', 'well to wheels', and 'seed to wheels'. They are all represented as 'cradle to grave'.

[b] GW = Global warming, AD = Abiotic depletion, OD = Ozone depletion, PO = Photochemical oxidation, A = Acidification, E = Eutrophication, HT = Human toxicity, ET = Ecotoxicity.

Table A.4
Impact assessment results with reference to conventional fossil oil system.

Class	References	Feedstock	Net energy output[a]	GHG emission[a]	Overall environmental impact[b]
Energy crops	[30]	Switchgrass	–	65% Less, E85	–
	[5]	*Brassica carinata*	Positive, 64%	145% Less, E85	Better
	[25]	Wood log	Positive, 86%	Less	–
	[6]	Soft wood	–	Less	–
	[14]	Switchgrass	Positive	Less	–
	[21]	Switchgrass	–	57% Less, E85	–
	[28]	Switchgrass	Positive, 80%	79% Less	–
	[53]	Poplar	Positive	51% Less, E85	Better
Biomass residues	[50]	Bagasse	Positive	Less	Better
	[4]	Wood residues	–	46–68% Less, E85	Better
	[49]	Flax shives	Positive	37% Less, E85	Better
	[22]	Corn stover	–	Less (mass allocation) more (economy allocation)	–
	[51]	Straw		Less	–
	[51]	Corn stover		Less	–
	[6]	Straw	–	Less	–
	[14]	Corn stover	Positive	Less	–
	[21]	Corn stoverh	–	65% Less E85	–
	[24]	Hard wood residues	–	Less, E85	–
	[24]	Soft wood residues	–	Less, E85	–
	[24]	Corn stover	–	Less, E85	–
	[37]	Straw	–	–	Better
	[29]	Corn stover	Positive, 80%	50% Less	–
	[29]	Wheat straw	Positive, 80%	50% Less	–
	[42]	Oil palm residues	Negative	More	–
	[43]	Sugarcane bagasse	Negative	More	–
	[52]	Hemp hurd	Positive	11% Less, E85	Better
	[54]	Alfalfa stem	Positive	88% Less, E85	Better
Biomass wastes	[23]	Biodegradable MSW	Positive	65% Less	Better
	[25]	Recycled paper	Positive, 73%	Less	–
	[19]	Biodegradable MSW	–	92% less	–
	[24]	Biodegradable MSW	–	Less, E85	–

MSW = municipal solid waste, – = not mentioned.

[a] Relative to the gasoline reference system at cradle to gate or cradle to grave boundaries, GHG = greenhouse gas.

[b] Based on the included impact categories.

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